BACKGROUND IN THE 25 FOOT CHAMBER
WHEN USED FOR NEUTRINO PHYSICS

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INTRODUCTION

For the purpose of assessing the effect of background particles in the bubble chamber, it is helpful to divide the background into charged particles and neutral particles. The latter category has precisely the same characteristics as a neutrino interaction or an interacting neutral which was produced in a neutrino reaction. The number of neutral background particles which can be tolerated is dependent on the reaction being studied. For this reason the level of the neutral background will be evaluated in terms of the contamination it introduces into the measurement of $d\sigma/dq^2$ for the reaction $\bar{\nu} + p \to n + \mu^+$. The charged-particle background can normally be eliminated during scanning, and its principal effect would be to slow down the scanning. A large background would be serious for pictures which were automatically scanned in terms of the computer time used to weed out the tracks.

CHARGED-PARTICLE BACKGROUND

The charged-particle background includes

(i) cosmic rays which enter the chamber during its sensitive time,

(ii) charged particles which are produced by neutrinos interacting

either in the muon shield or the bubble-chamber magnet coils,

(iii) charged particles produced at the proton target of the neutrino

beam which scatter around the shield.

The cosmic-ray flux with a kinetic energy greater than 300 MeV

is 0.82×10^{-2} particles cm^{-2} sec^{-1} sr^{-1} at normal incidence. If the

chamber is sensitive for 10 milliseconds and no allowance is made for

muons stopping in the shielding surrounding the bubble chamber, the

number of cosmic-ray tracks which would appear in a picture would be

90. If it is assumed that the chamber is placed underground and sur-

rounded by 5 feet of heavy concrete shielding, the minimum cosmic-ray

energy needed to enter the detector would be 1 BeV, and the number of

tracks per picture would be less than 30, which is tolerable.

<u>Muons.</u> The most serious charged-particle background is due to

muons which are generated by neutrinos in the downstream end of the

muon shield. The momentum of muon produced in an elastic neutrino

collision such as $\nu + n \rightarrow \mu^{-} + p$ is given by P_{μ}:

$$P_{\mu} = k \left[1 - \frac{|q^{2}|}{2kM} \right] , \qquad (1)$$

where k is the energy of the incident neutrino, q_{0}^{2} is the momentum

transfer to the lepton, and M the mass of the nucleon. If one assumes

the elastic form factors are all described by the same dipole factor $F(q^{2})$

$$F(q^2) = \left[\frac{1}{1 + q^2/q_o^2}\right]^2 \quad, \quad q_o = 0.750 \text{ BeV/c}, \qquad (2)$$

then q^2 is effectively limited to q_o^2. Since most of the suggested beams

have very few neutrinos with less than 3 BeV, the muon will have 95%

or more of the neutrino energy at the time it is produced. The average

production angle of the muon, θ_μ, measured with respect to the neutrino

direction when $F(q^2)$ is given by (2) is

$$\tan \theta_\mu \approx (0.6q_o)/k = 0.45/k. \qquad (3)$$

The angular dispersion of the muons at 3 BeV is 9°. When the effect of

the Fermi motion in the nucleus is considered the angular distribution is

broadened. Nevertheless, nearly all of the muons produced by neutrinos

in the end of the shield will enter the fiducial region of the bubble chamber

if it is less than 15 meters from the end of the shield. While this result

was obtained for elastic scattering, very nearly the same conclusion can

be drawn for the case when the outgoing nucleon is accompanied by one

or more pions. The amount of shield which can be regarded as a muon

source is equal to the range of muon with the energy of the parent

neutrino. Above 3 BeV the neutrino cross section on nucleons is largely

inelastic and as a result the average cross section per nucleon in a

nucleus is roughly equal to the cross section on protons. If the W exists

and its mass is small enough to permit coherent production on nuclei at

a particular neutrino energy, then above this energy the production per

nucleon in the shield will be much larger than on protons. Since the

mass of W should be larger than 3 BeV, this process would be important

above 50 BeV. The fraction of neutrinos above 50 BeV is less than 1%,

and as a result this process will make a small contribution. Excluding

W production the number of neutrino induced muons which can enter the

bubble chamber per neutrino interaction in the fiducial region is

$$\frac{N_\mu}{N_\nu} = \frac{K}{\left(\frac{dE}{dx}\right)_s \, \rho_{H_2} \, L} = 13 \, K, \tag{4}$$

where dE/dx is the minimum ionization loss which is taken to be

1.5 MeV/gram. L is the chamber fiducial length which is 6 meters,

ρ_{H_2} the density of liquid H_2.

On the basis of L. Hyman's neutrino spectrum for a CKP meson-

production spectra, 400-meter decay length and a 150-meter iron shield,

the number of background muons made in the shield per interaction in

the 25-ft chamber is 130. The average muon momentum is 7 BeV. It

has been suggested that the neutrino experiment take a full pulse of

5×10^{13} protons, rather than a fraction of each pulse. During this kind

of operation with a 60% efficient target and a decay and shield length as

in Hyman's beam, an integrated neutrino flux of 3.6×10^{12} neutrinos

would strike the bubble chamber. If the average cross section is

2×10^{-38} cm^2 for the energy range of that spectrum, the number of

neutrino events per picture is 1.5: $N_\nu = (0.12)(5 \times 10^{13})(0.60)(0.06)$

$(600)(6 \times 10^{23})(2 \times 10^{-38}) = 1.5$. On the basis of this rate there would

be 200 muon tracks per picture. This background is regarded as ex-

cessive and should be reduced. Since 80% of the muons have an energy

of less than 10 BeV, this fraction can be swept away by magnetic

deflection. To account for the expected rise of the total cross section

with energy, it was assumed to be given by

$$\sigma_r = (0.6 \times 10^{-38})(1 \times N_\pi) \text{ cm}^2/\text{nucleon}. \tag{5}$$

N_π is the pion multiplicity. The requirements for an air gap magnet or

a block of magnetized iron to sweep the muons away are discussed

later.

While the muons produced in the shield can be removed by mag-

netic deflection, the muons produced in the portion of the magnet coils

upstream of the fiducial region of the bubble chamber cannot be swept

away. There will be 5 neutrino-induced muons which enter the bubble

chamber from the coils per interaction in the chamber. In addition, there

will be another 2.5 muons per interaction in the chamber which come from

the coil support structure. The spectrum of these muons is identical to the

spectrum of the muons produced in the hydrogen, since the average

energy loss is of the order of 0.5 BeV. One expects about 10 muon

tracks per picture from this source, which is not a serious background.

The portion of the coils which is not upstream of the fiducial volume is not a muon source, since the muons go forward, but it is a source of pions and nucleons which are associated with the recoiling nucleus. In the case of elastic scattering of free nucleons the recoil nucleon angle θ_n is given by

$$\cot \theta_n = \frac{1}{2} \left(\frac{k + M}{kM} \right) \left[\frac{|q^2|}{1 - \frac{|q^2|}{4} \left(\frac{2kM + M^2}{(kM)^2} \right)} \right]^{1/2} , \qquad (6)$$

for $k >> M$ the average value of $\cot \theta_n$ for the case of the dipole form factors is

$$\cot \theta_n = \frac{0.6 q_o}{2m} \approx 0.24 . \qquad (7)$$

Thus, the nucleons come out within an equatorial zone with a half angle of $15°$, whose axis is perpendicular to the neutrino beam.

Another source of muons will be from prompt decay of pions and kaons that are produced at moderate angles with respect to the proton beam. These muons can be minimized by keeping the neutrino beam and the bubble chamber underground. In this manner, muons can only reach the bubble chamber by first emerging from the earth, then scattering in the air, and finally going through the earth again. Paths for which the amount of earth traversed is less than the muon range require three large angle scatters one of which is in the air.

As will be discussed later, the number of neutrons will amount to
10 per picture. The number of charged hadrons will be at least an order
of magnitude less since they will almost always stop in the coils. This
is not true of the neutral particles which are discussed in the next section.

Neutral-Particle Background

The principle sources of neutral background are

(i) high-energy neutrons produced at the target which scatter
around the shielding,

(ii) neutrons, neutral k mesons, and γ rays which are produced
in shielding and the magnet coils by neutrino interactions.

If two neutrons which come from the target with an energy greater
than 5 BeV enter the 25-ft bubble chamber per pulse, they will produce
per picture as many events with the characteristics of a neutrino event
as the actual number of neutrino events. Since the bubble chamber does
not provide any discrimination between fast muons and pions, all of the
events in which the outgoing nucleon is a neutron will have the same
properties as neutrino events. For example the reaction

$$n + p \rightarrow N_o^* + p$$
$$\quad \quad \quad \vdash \rightarrow \pi^+ \pi^- n \quad .$$
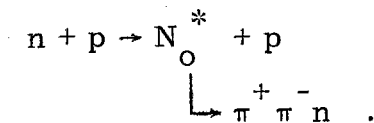
It is assumed that in about half the interactions a neutron is em-
itted and hence, $\sim 10^{13}$ neutrons are produced per pulse and a reduction

of a factor of 10^{15} is needed. If both the bubble chamber and the proton

beam target are underground, this attenuation factor can be achieved

easily. Nevertheless, it is difficult to imagine that an occasional neutron

will not get through and as a result it would seem desirable to provide

either a set of counters or spark chamber outside of the bubble chamber

to provide identification of the muon. The limitations of these two systems

are discussed later.

The neutrals which are produced in the coils by neutrinos are

emitted at an average angle of 70° to the neutrino beam. As a result

neutrons which are produced in the shield or the upstream portion of the

magnet coils will undergo many nuclear interactions before emerging.

To determine the neutron background it is only necessary to determine

the number of neutrons produced in the portion of the coils which are

parallel to the neutrino beam. If it is assumed that a neutron made at

an angle of more than 45° to the coil radius does not emerge from the

coil, one half of the coils can contribute to neutron production. The

average probability of a neutron entering the bubble chamber, ignoring

nuclear interactions, is 1/6. The number of these neutrons which con-

tribute to the background can only be discussed in term of the reaction

which is being studied. The reaction is taken to be $\bar{\nu} + p \rightarrow \mu^+ + n$ with

the detection of the neutron by a subsequent np scattering. If the energy

of the neutron is to be determined, the proton recoil track must be longer

than 1 cm. The proton momentum for this range is 140 MeV/c and thus,

the typical neutron momentum must be 200 MeV/c, corresponding to a

q^2 of $(200 \text{ MeV/c})^2$.. For this and larger q^2, $d\sigma/dq^2$ is sensitive to both

the weak magnetism term and the form factor. Presumably one would

like to measure $d\sigma/dq^2$ for smaller q^2 in order to extrapolate to $q^2 = 0$.

It is possible to distinguish an elastic event on the basis of coplanarity

of the muon and neutron, if the proton recoil can be seen. Assuming that

one can see proton tracks 1-mm long or longer, the proton momentum

must be at least 75 MeV/c. The typical neutron momentum for which

detection is possible would be 100 MeV/c. If one used only coplanarity,

the range of q^2 from $(100 \text{ MeV/c})^2$ to $(200 \text{ MeV/c})^2$ can be included. In

the region $(100)^2 < q^2 < (200)^2$, $d\sigma/dq^2$ changes by only 15% due to the

form factor, and the weak magnetism contribution is less than 7%. On

this basis, any neutron with an energy greater than 3 MeV/c can con-

tribute to the contamination of $d\sigma/dq^2$. On the basis of this restriction

and the fact that the average kinetic energy of the neutron is 75 MeV,

the thickness of the coils that can contribute to the neutron background

equals 3.5 interaction lengths. The amount of material from which

neutrons can manage to enter the chamber is 7.4×10^7 grams. This

estimate includes the interactions made in the support structure of the

coils. The probability for an n-p scatter due to a neutron produced in

the coils is approximately twice as great as it is for a neutron produced

in the bubble chamber. Thus, the ratio number of proton recoils from

background, N'_{nr}, to the number of proton recoils due to the desired

neutrino event, $N'_{e\ell}$, is

$$\frac{N'_{nr}}{N_{e\ell}} = \left[\frac{1}{6} \times \frac{7.4 \times 10^7}{4.2 \times 10^6} \times 2 \times \frac{2}{0.6}\right] = 20. \qquad (8)$$

During each pulse approximately 10 neutrons will enter the chamber and five of these will give visible proton recoils. This number is not serious since both the scattering plane and the direction of the neutron are defined by the incoming neutrino and the outgoing muon. The uncertainty in the orientation of the scattering plane is

$$\delta\theta_n = \frac{1}{\sin\theta_\mu} \left[\frac{(\delta\theta_\mu)^2 + (\delta\theta_\nu)^2}{2}\right]^{1/2}, \qquad (9)$$

where $\delta\theta_\nu$ and $\delta\theta_\mu$ are the uncertainties in the neutrino and muon direction. The former is 4 mrads and the latter, which is due to multiple scattering, is less than 10^{-3} radians. The angle the neutron makes in the scattering plane has been given before by (6). From (6) the uncertainty of this angle for small q^2 is

$$\delta\theta_\nu = \left(\frac{k + M}{2M}\right) \left[\frac{(\delta\theta_\nu)^2 + (\delta\theta_\mu)^2}{2} + \sin^2\theta_\mu \left(\frac{\delta p_\mu}{p_\mu}\right)^2\right]^{1/2}. \qquad (10)$$

$\delta p_\mu / p_\mu$ is the momentum resolution of the muon, which is assumed to be 1%.

Allowing twice these angles for a limit of error the solid into

which the neutron can go is

$$d\Omega = \left(\frac{k + M}{2M}\right) \frac{k}{\sqrt{q^2}} \quad (4 \times 10^{-5}) \; . \tag{11}$$

Since the presence of recoil protons is uniform throughout the

chamber, the ratio of background contamination to $d\sigma/dq^2$ is

$$f_b = \frac{3}{8\pi} \frac{k + M}{2M} \frac{k}{\sqrt{q^2}} N'_n \frac{(d\sigma/dq^2)_{in}}{(d\sigma/dq_o^2)_{e\ell}} \frac{1}{f_d} \times 4 \times 10^{-5} . \tag{12}$$

N'_n is the five background proton recoils per picture. $(d\sigma/dq^2)_{in}$

is the cross section for the process $\bar{\nu} + p \rightarrow \mu^+ + n + 1\pi_o$, and $(d\sigma/dq^2)_{e\ell}$

is the cross section for $\bar{\nu} + p \rightarrow \mu^+ + N/f_d$. The detection efficiency for

neutrons is 25%. For $k = 5$ BeV, and $\sqrt{q^2} = 100$ MeV/c, the background,

f_b, is 0.030. Since the rate for this experiment is one useful event per

three pulses, the presence of 5 proton recoils per picture is not serious.

At an energy of 20 BeV, the background becomes serious at the minimum

q^2. An accurate measurement of $d\sigma/dq^2$ will require a large enough

q^2 so that the neutron energy can be determined from the proton recoil

in order to suppress the background. This will restrict the schemes in

which $d\sigma/dq^2$ at small q^2 is to be used to measure the neutrino flux to

energies below 20 BeV.

In addition to external background, the reaction $\bar{\nu} + p \rightarrow \mu^+ + n + \pi^o$

will fake an elastic event when the π^o is either emitted in the same di-

rection as the muon or the same direction as the neutron. If the π^o

comes from an N^* decay the probability the decay be within the proper

kinematic limits is roughly 3%.

A background of 5 proton recoils per picture will limit the ability

to study a process such as $\bar{\nu} + p \rightarrow N^{*o} + \mu^+$; $N^{*o} \rightarrow n + \pi^o$. Since the

kinematics place very little limit on the direction or the energy of the

π^o, most background neutrons will give a fit. The contamination will

probably be larger than the yield from the reaction. A similar set of

arguments can be advanced to show the background of neutral K's and

Λ's will not provide a serious contamination to the reactions in which

there are no missing neutrals. Consequently it seems that with the

exception of the muon background most background sources are tolerable.

It is assumed that the neutron background due to skyshine neutrons can

be made small. If this is twice as large as the neutrino contribution,

then the elastic events will have a large contamination, and the study

of inelastic events with a missing neutral will be impossible. Table I

presents a summary of the particle background per picture when 3×10^{13}

protons interact in the target (see following page).

Magnet Deflection of Neutrino-Induced Muons--"Flux-Grabber"

Two proposals have been put forth to eliminate the neutrino-

induced muons; they are an iron return path for the bubble chamber

Table I. Background Events per 3×10^{13} Protons.

1.	Cosmic-ray tracks	30
2.	Muon tracks from neutrino interactions in the shield	200
3.	Muon tracks due to neutrino interactions in the coils and support structure	10
4.	n-p scatters due to neutrino interactions in the coils and support structure	5
5.	n-p scatters due to skyshine neutrons	1
6.	Neutral strange-particle decays in the chamber from neutrino interactions in the coils	<1

magnet and a magnetized iron shield. By using the magnetic field of the
bubble-chamber magnet, as proposed by Stevenson, it is possible to
obtain a 167-kG-m magnetic field with a 6 meter aperture. It would
bend all particles through an angle $\theta_b = 5/p$ radians. For momenta
below 9 BeV the particles would be deflected away from the bubble
chamber, provided there were a 10 meter lever arm from the center of
the air gap to the front of the bubble chamber. At 15 BeV approximately
2/3 of the particles are deflected out. At 20 BeV 50% of the muons are
deflected out, beyond 40 BeV the deflector has very little effect. Never-
theless, this technique would reduce the number of tracks to less than
25 per picture which is a manageable number.

The use of a 10-meter long magnetized iron plug will also reduce
the flux of muons. While it will be less efficient than the flux-grabber
for the same lever arm, the leverage can be made 40 meters without

changing the neutrino flux. If the lever arm of the flux-grabber is doubled, the amount of iron is doubled as is the cost. For a muon which enters the magnetized iron shield with an energy k and traverses Z_o meters of shield, the angle by which the particle is deflected by the magnetic field is θ_b:

$$\theta_b = 0.3 \ B \ \left(\frac{dE}{dx}\right)^{-1} \ \ell n \ \left[k / \left(k - \frac{dE}{dx} Z_o \right) \right] \ . \quad (13)$$

The multiple coulomb scattering while traversing the shield is

$$\left\langle \theta_c^2 \right\rangle^{1/2} = \frac{15}{\sqrt{k \left(k - \frac{dE}{dx} Z_o \right)}} \sqrt{\frac{Z_o}{X_o}} \ . \quad (14)$$

X_o is the radiation length in meters and dE/dx is the ionization loss in GeV/m. For a given deflection angle, $\left\langle \theta_b \right\rangle$, all muons of energy k will be deflected by this angle or more if Z_o is greater than

$$Z_o = \frac{k}{dE/dx} \left[1 - e^{-\left[\left\langle \theta_b \right\rangle \frac{dE/dx}{0.3B} \right]} \right] \ . \quad (15)$$

A rough estimation of the muon flux emerging from the shield, using (15), Z_o = 40 meters, and L. Hyman's spectra, yields 38 muons per pulse. The magnetized block is assumed to be 6-meters wide and 10-meters long. It is assumed there is no earth surrounding the magnetic shield.
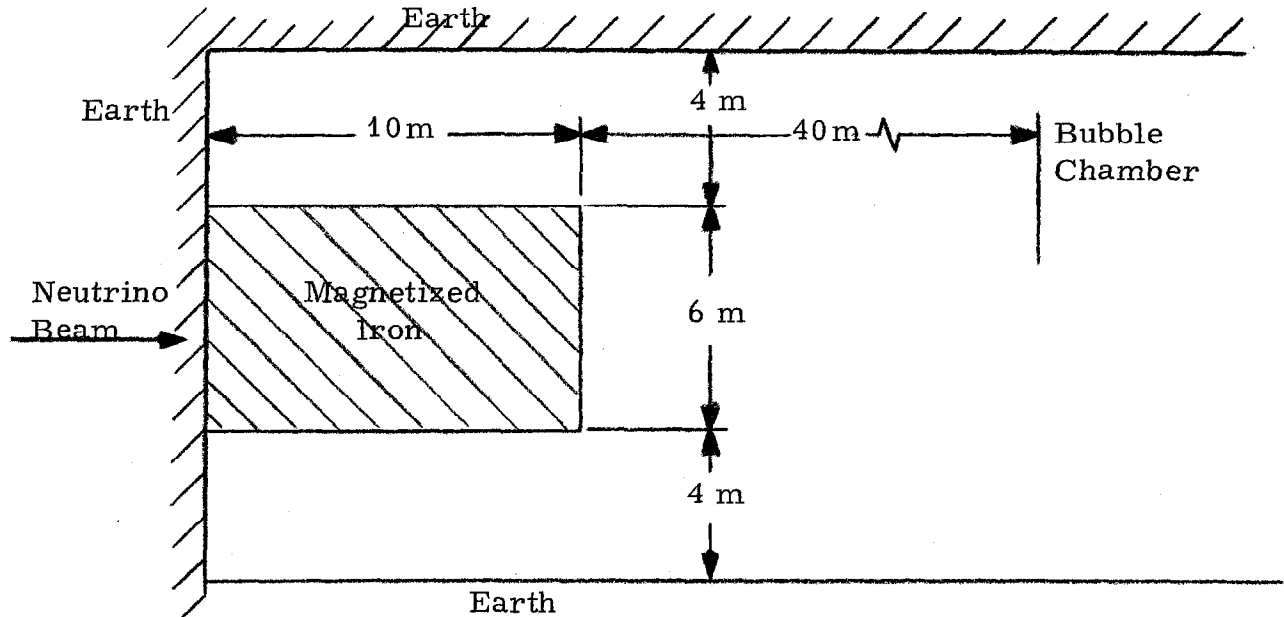
By evaluating Eq. (14) it can be shown that the total multiple scattering

is less than the average production angle, 0.45/k, for all the k less

than 30 BeV. For this reason, multiple scattering was neglected in the

calculations.

Muon Identification

As was pointed out earlier, without a means of muon identification

a very small flux of high-energy neutrons (2 per pulse) can completely

contaminate all experiments in the 25-ft chamber. In all previous

neutrino experiments, muons and pions were separated by their range

in either aluminum spark chambers or a heavy liquid. If the bubble

chamber is to take a full beam pulse which lasts 20×10^{-6} seconds, then

the use of spark chambers will be ruled out. This is because there will

be 20 to 50 muon tracks which go through the chamber. The chamber

must not only remain sensitive for 20 microseconds but it must have a

uniform efficiency for all tracks throughout the 20 microseconds. While

the former is possible the latter is doubtful.

A second alternative which would not suffer from this difficulty

would be a counter hodoscope. Let the downstream portion of the coils

be surrounded by a set of counters, each 12 in. wide and 4 meters long,

viewed by a phototube at each end. The long dimension of the counter is

vertical. Each counter subtends an angle of $\pm 2°$ in azimuth from the

center of the bubble chamber. The position of the particle along the

4-meter length of the counter can be determined to 1 foot by measuring

the time difference between the arrival of the light pulses at either end

of the counter. At each 4° interval along the perimeter of the bubble

chamber coils three such counters are placed; between successive

counters two interaction lengths of nonmagnetic material are placed.

It should be noted that between the bubble chamber and the outside there

are the coils and the support structure. The coil thickness corresponds

to 6 nuclear interaction lengths and the support structure is on the av-

erage 87 gm/cm^2 of stainless steel. Consequently, very few gamma

rays can emerge to be seen as showers in a spark chamber. Most

γ's will have lost 75% of their energy if they go through the supports.

Since the coils correspond to 50 radiation lengths no γ-ray shower can

emerge. A triple coincidence among a set of three counters signifies

the presence of a muon. Since the counters define the particle to within

1 square foot and since the background muons are spread over 100 sq ft

the chance of ambiguity with a background muon is 1 in 2. This can be

reduced to essentially zero by noting that all of the 50 straight-through

tracks that occur during the beam spill (the use of the flux grabber is

assumed) are visible in the chamber and are muons. As a result, one

can predict what counter should be hit and determine the number of

times each counter is hit. Since the number of background counts in a

given counter can be determined, there is no ambiguity in whether a

real event gave a count or not.

Some cosmic rays are nearly horizontal and will give a count

during the beam spill. Since the beam muons must extrapolate back to

the shield and since the bubble chamber is below ground one would expect

a very small contribution. By recording all events during the chamber

sensitive time this problem is eliminated, although it is not clear that is

necessary.

A second problem arises if a charged π charge exchanges and the

γ-ray shower penetrates all three counters. While a more detailed study

is necessary to determine what fraction of muon tracks are properly

identified, it should be better than 99%. It is assumed that the counter

hodoscopes are fed into a set of registers and that when any set of two

of these counters counts in a module all of the counters are strobed into

the registers. The contents of the registers are loaded into a small

computer and then on to tape. It is assumed that the same computer

is used to monitor the muon flux in the shield near the proton target

and the proton target itself.